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PERFORMANCE CHARACTERISTICS OF MIXED-FLOW IMPELLER AND VANED DIFFUSER WITH SEVERAL MODIFICATIONS

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MEMORANDUM REPORT

PERFORMANCE CHARACTERISTICS OF MIXED-FLOW IMPELLER AND VANED DIFFUSER WITH SEVERAL MODIFICATIONS

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SUMMARY

The performance of a mixed-flow impeller and vaned diffuser unit with several modifications was investigated in an NACA variable-component supercharger test rig. The investigation covered impeller tip speeds from 800 to 1200 feet per second over the range of air flows from wide-open throttle to incipient surge. Several different frontal clearances were tried, surveys were taken to determine the losses in the various components, and, finally, two vaneless extensions of different diameter were added to the diffuser.

The results showed the supercharger to have a peak efficiency of 0.77 and a peak pressure coefficient of 0.61 with the impeller frontal clearance at 0.035 inch. The supercharger was fairly sensitive to clearance, the peak efficiency falling off about two points at a mean clearance of 0.070 inch. The use of the vaneless extension to the standard diffuser increased the efficiency to 0.80.

INTRODUCTION

A centrifugal supercharger has been constructed having an impeller incorporating flow passages that change from the inlet to the exit of the impeller more gradually than the conventional centrifugal impeller. Performance investigations conducted by the manufacturer on this supercharger showed an efficiency of over 80 percent, which is appreciably higher than that of any supercharger currently in use with reciprocating engines. Furthermore, this high efficiency was obtained at a very high load coefficient. In order to verify the results of these tests and to obtain more complete information on the impeller and diffuser used in this supercharger, the NACA initiated a study of the supercharger to determine its original operating characteristics along with the performance resulting from several design changes. The supercharger modifications include changes in impeller frontal clearance and the addition of vaneless extensions of different diameter to the standard vaned diffuser.

SUPERCHARGER

The supercharger impeller used in this investigation is shown in figure 1. It is a single shrouded impeller having an inlet diameter of $8\frac{1}{4}$ inches and a tip diameter varying along the axial length from 11.015 to 11.241 inches. There are 23 blades with scallops on the periphery between the blades. The blades are so designed that their curvature is gradual and extends over the entire length. They are so constructed that the centrifugal forces are taken in tension and introduce no bending moments. The passage is so shaped that the flow has both a backward and an axial component of velocity along the radius. For this reason the impeller is usually referred to as a "mixed-flow" impeller. Unlike the conventional centrifugal impeller, the blades do not have curved sections at the inlet usually referred to as inducers.

The diffuser used in conjunction with the impeller is shown in figure 2. It has an inner diameter of 11.8 inches, an outer diameter of 17 inches, and has 14 equally-spaced vanes. An assembly drawing of the impeller-diffuser combination with the over-all dimensions is shown in figure 3.

TEST SETUP AND PROCEDURE

The impeller and diffuser were tested in the NACA variable-component supercharger test rig, a description and photographs of which are given in reference 1. A photograph of the setup is shown in figure 4.

The supercharger was originally set up with a mean frontal clearance (running clearance) of 0.070 inch and run at tip speeds of 800, 900, 1000, 1100, and 1200 feet per second over the range of air flows from wide-open throttle to surge point with the outlet pressure held constant at 40 inches of mercury absolute. The impeller for these first tests ran out of true at the blade tips thus resulting in a minimum frontal clearance of 0.056 inch and a maximum of 0.084 inch, giving a mean clearance of 0.070 inch. All the measurements recommended in reference 2 were taken. Survey tubes were then installed at the impeller tip, in the diffuser outlet, and at a point 2 inches from the diffuser exit. Runs were made at 800 and 1100 feet per second during which both the surveys and the over-all data were taken.

A new front shroud was installed with a uniform frontal clearance of 0.035 inch, which was the smallest permissible for safe operation in the unit being studied. (The impeller was designed for a clearance of 0.025 inch.)

During some additional tests a blade failure occurred in the impeller. A new impeller was obtained and machined to the exact size of the original impeller, which it replaced. After machining, the impeller had the same shape passage as the first. Tests were then made to see if the characteristics of the original and replacement impellers agreed.

Finally, tests were made with an extension on the diffuser. This extension consisted of two parallel, flat, annular plates, so mounted that their axial depth was the same as the diffuser exit depth. The effect was a vaneless diffuser extension of the standard diffuser. Runs were made with different extensions, one of 27 inches outside diameter and the other of 35 inches, at 900 and 1100 feet per second.

MEASUREMENTS

Figure 5 is a sketch showing the location of the points at which pressure and temperature measurements were made in the investigation of the over-all performance of the unit. Static pressures and total pressures were measured with mercury manometers and temperatures were measured with iron-constantan thermocouples.

The location of the survey tubes in the second test is shown in figure 6. These tubes were arranged for axial traverse and for variable angle with the radial and were divided into two groups. One group A was located at a diffuser passage that discharged directly toward a discharge duct, and the other group B was located approximately 90° away. A survey with a given tube consisted of reading the maximum total head at five points across the passage. The average total pressure was then obtained by a planimeter integration of a curve drawn through these points. The total temperature throughout the entire outlet system was assumed to be the same and was taken as the total temperature in the discharge pipes.

Measurements in the final tests were the same as in the first test.

COMPUTATIONS

The method used in finding the characteristics of the supercharger is given in reference 2. The temperature recovery coefficient for the thermocouples was taken as 0.83. The largest diameter of the impeller was used for finding the pressure coefficient.

The angle at which the air entered the diffuser was found by the use of the following equations:

$$V_{g_{t_1}} = \frac{gH}{V} \tag{1}$$

where

$V_{g_{t_1}}$ the tangential velocity of air leaving impeller, feet per second

g the acceleration of gravity, taken as 32.174 feet per second per second

V the impeller tip speed, feet per second

H the increase in total enthalpy per unit mass, foot-pound per pound

$$V_{g_{t_1}} r_1 = V_{g_t} r \tag{2}$$

where

V_{g_t} the tangential velocity of air entering diffuser, feet per second

r the radius of diffuser entrance, feet

r_1 the radius of impeller, feet

$$Q = A\,V_g \tag{3}$$

where

Q the volume of air entering diffuser, cubic feet per second

A the area perpendicular to the direction of flow, square feet

V_g the absolute velocity of air entering diffuser, feet per second

$$\sin\ \theta = \frac{A}{A_1}\ ;\ \cos\ \theta = \frac{V_{g_t}}{V_g} \qquad (4)$$

where

θ	the angle at which the air enters the diffuser, degrees
A_1	the area perpendicular to the radius, square feet

$$T_t - T_s = \frac{V_g^2}{2g\ \frac{\gamma}{\gamma-1}\ R} \qquad (5)$$

where

T_t	the total temperature of the air, °F absolute
T_s	the static temperature of the air, °F absolute
γ	the ratio of specific heats, taken as 1.3947
R	the gas constant, taken as 53.50

$$\frac{T_t}{T_s} = \left(\frac{P_t}{P_s}\right)^{\frac{\gamma-1}{\gamma}} \qquad (6)$$

where

P_t	the total pressure of the air, pounds per square foot
P_s	the static pressure of the air, pounds per square foot

$$P_s\ Q = WR\ T_s \qquad (7)$$

where

W	the weight of air flowing, pounds per second

Computations of the angle involve a trial and error solution.

RESULTS AND DISCUSSION

The performance of the mixed-flow impeller and vaned diffuser unit with a mean impeller frontal clearance of 0.070 inch is presented in figures 7 and 8 where adiabatic efficiency and pressure coefficient, respectively, are plotted against load coefficient. The maximum over-all efficiency was about 0.75 at impeller tip speeds of 900, 1000, and 1200 feet per second. At tip speeds of 800 and 1100 feet per second the peak efficiency was very little lower. As with the efficiency, the pressure coefficient was nearly the same at all tip speeds. The maximum pressure coefficient was 0.59 from tip speeds of 800 to 1000 feet per second. At tip speeds of 1100 and 1200 feet per second the peak pressure coefficients were only about one point lower.

Surveys were made at the impeller outlet, diffuser outlet, and 2 inches from the diffuser exit to obtain an indication of the performance of the components of the unit and what results might be expected from various modifications. Over-all measurements were taken at the same time as a check. The results of these surveys are shown in figure 9. The surveys were divided into two groups, one located at a diffuser passage that discharged directly toward a discharge duct, the other located approximately 90° away. The data from each of these groups were separately calculated, and both sets are plotted in figure 9 with the same symbols. As might be expected, the points are somewhat scattered, and the data cannot be considered too accurate because of the difficulty of taking measurements in the highly turbulent air in the diffuser. The data, in particular, taken in the diffuser exit were scattered and the two groups gave separate curves at high load coefficients. The curves do, however, give an indication of the losses in the various components.

The results plotted in figure 9 show that the impeller efficiency is very high, reaching a peak of about 0.92 at 800 feet per second and 0.88 at 1100 feet per second. The largest loss in the unit is apparently between the diffuser exit and 2 inches beyond the exit. This loss is probably due to several reasons. First, the diffuser has a small expansion ratio, the ratio of the exit area to the inlet area being less than 2:1, and is designed for use in conjunction with a scroll-type outlet. Second, the area of the collector is very large, causing a considerable loss due to sudden expansion.

As there is also a large loss in the diffuser and as the curves for the impeller efficiency and over-all efficiency do not peak at the same load coefficient, it was suspected that the angle at which the diffuser was set did not coincide with the angle at which the air entered at the highest impeller efficiency. The angle was therefore calculated from the data and is also plotted against the load coefficient in figure 9. The fact that the maximum over-all efficiency occurs at an angle of 20°, the angle for which the diffuser was designed, indicates that the data are fairly reliable and that the correct angle of design should be about 24° as the impeller efficiency peaks at this point.

As there is certainly a loss in the diffuser passages it is difficult to estimate the gain that might be obtained by changing the entrance angle. This increase, being only a fraction of the difference shown, would probably be small and may only tend to shift the operating point without increasing the peak, although the efficiencies at the higher load coefficients should show a substantial increase.

The results of the tests with the frontal clearance reduced to 0.035 inch are plotted in figures 10 and 11, and a comparison is made with the original tests in figures 12 and 13. From these curves it can be seen that the efficiency is increased over the original by two or three points, the maximum efficiency being 0.77 at 900 feet per second.

The peak efficiency falls off very little with speed, decreasing from 0.77 at 900 feet per second to 0.76 at 1200 feet per second. The curves show that the frontal clearance has an appreciable effect on the supercharger performance although the effect is not so great at 1200 feet per second as at lower speeds.

The curve of adiabatic head against the load coefficient at all speeds for the 0.035-inch clearance test is shown in figure 14. On this curve the efficiencies are plotted as contours, and the point of maximum efficiency is seen to be at 900 feet per second at a load coefficient of about 0.225.

The pressure ratio at 60° F is plotted against the load coefficient in figure 15. The maximum ratio obtained was 2.35 at 1200 feet per second at a load coefficient of 0.25. The results of the tests run to compare the characteristics of the original and replacement impellers are shown in figure 16. The curves show that the performance of the two impellers is identical.

In order to reduce the large loss due to sudden expansion at the diffuser exit, a vaneless extension was added to the diffuser. Two sizes were tried, one 27 inches in diameter and the other 35 inches in diameter. The test results with these extensions are plotted in figure 17 and compared with the previous tests. The use of the 27-inch-diameter extension increased the peak efficiency at 900 feet per second from 0.77 to 0.80 and at 1100 feet per second, from 0.76 to 0.79. The peak pressure coefficient was increased about two points in both cases. No additional increase in efficiency was obtained by using the larger extension. As the manufacturer used a scroll-type outlet that eliminated the sudden expansion, the results are comparable and the value of 80 percent obtained by the NACA approaches the value obtained in his tests.

In general, it might be said that the supercharger was a very smooth-running machine and that pulsation was so gentle that at the lower speeds it was difficult to detect. Even at the high speeds it was not violent and should not cause undue stresses or appreciably affect the operation of an engine.

The characteristic curves are fairly flat over most of the range, although at 1200 feet per second they become steeper.

The pressure coefficient is about eight points lower than the conventional supercharger which means that to obtain the same pressure ratio the impeller must turn about 1.06 times as fast.

CONCLUSIONS

1. The mixed-flow impeller and vaned diffuser unit showed a peak efficiency of 0.77 and a peak pressure coefficient of 0.61 at a tip speed of 900 feet per second with the impeller frontal clearance set at 0.035 inch. The efficiency at 1200 feet per second fell only one point to 0.76.

2. The supercharger showed itself to be fairly sensitive to clearance, the peak efficiency being about two points lower at a mean frontal clearance of 0.070 inch.

3. Surveys in the impeller and diffuser showed that the impeller efficiency was very high, being about 0.92. The surveys also showed that there was a large loss in the test rig collector case caused by the sudden expansion as the air left the diffuser and a large loss in the diffuser itself.

4. The use of a vaneless extension on the original diffuser increased the peak efficiency to 0.80 and substantiated the expansion loss indicated by the surveys. As the manufacturer's tests were run with a scroll-type outlet which also

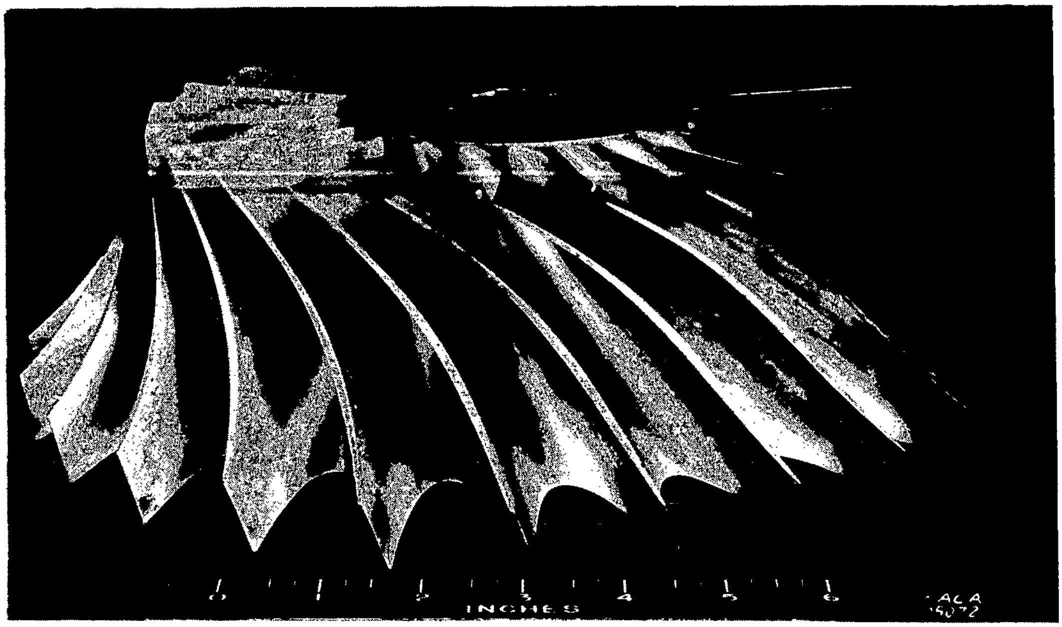
eliminates the sudden expansion, the tests are comparable and check as to efficiencies of 80 percent.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 11, 1942.

REFERENCES

1. Ellerbrock, Herman H., Jr., and Goldstein, Arthur W.: Principles and Methods of Rating and Testing Centrifugal Superchargers. NACA ARR Feb. 1942.

2. NACA Subcommittee on Supercharger Compressors: Standard Procedures for Rating and Testing Centrifugal Compressors. NACA ARR No. E5F13, 1945.



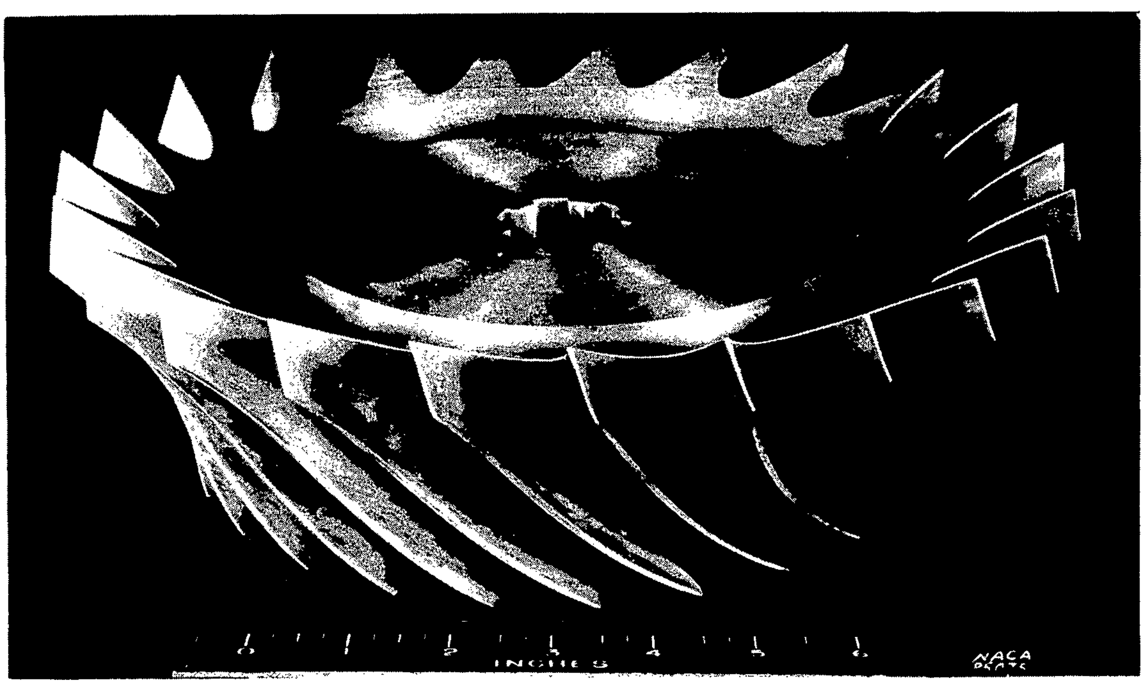


Figure 1. - Mixed-flow impeller.

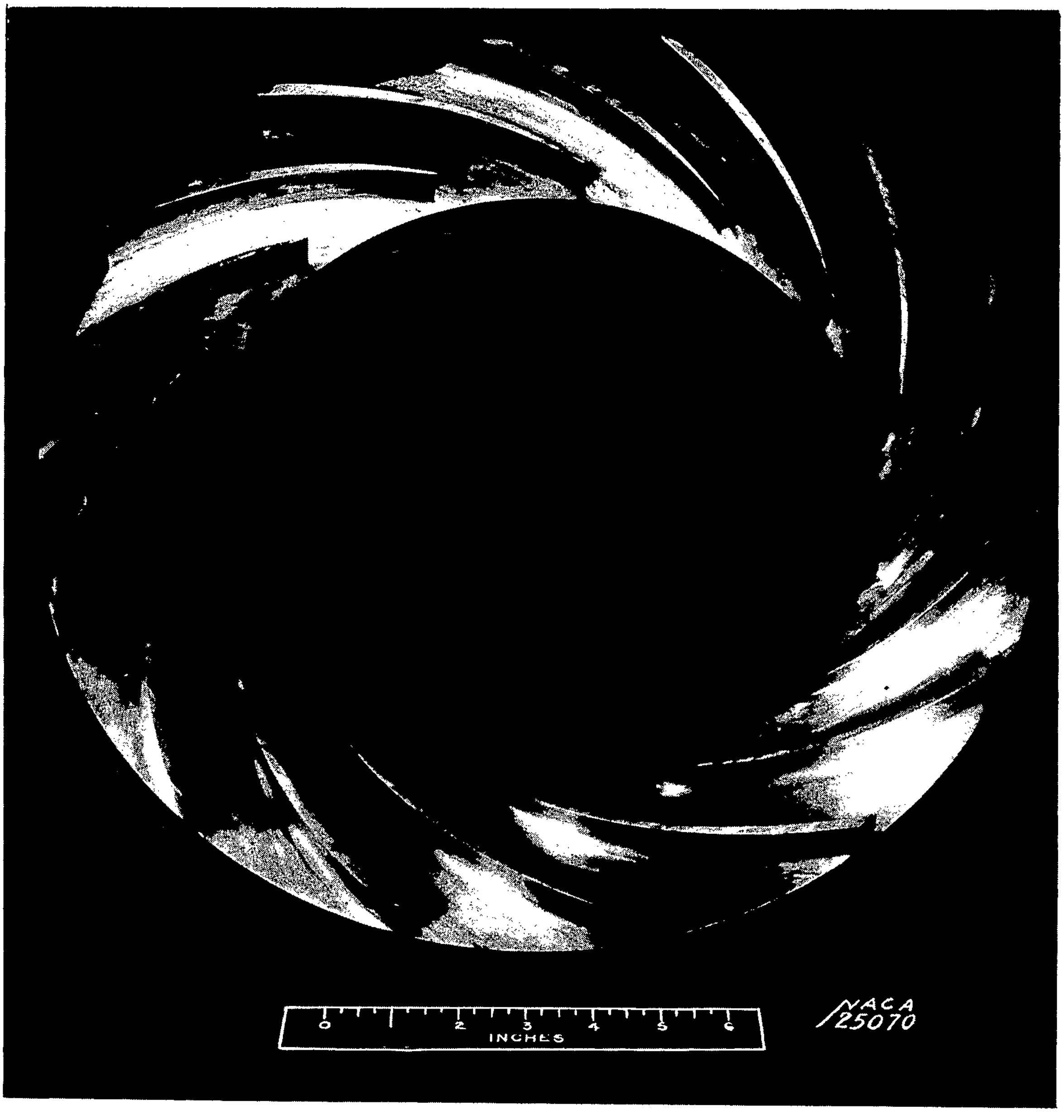


Figure 2. - Vaned diffuser.

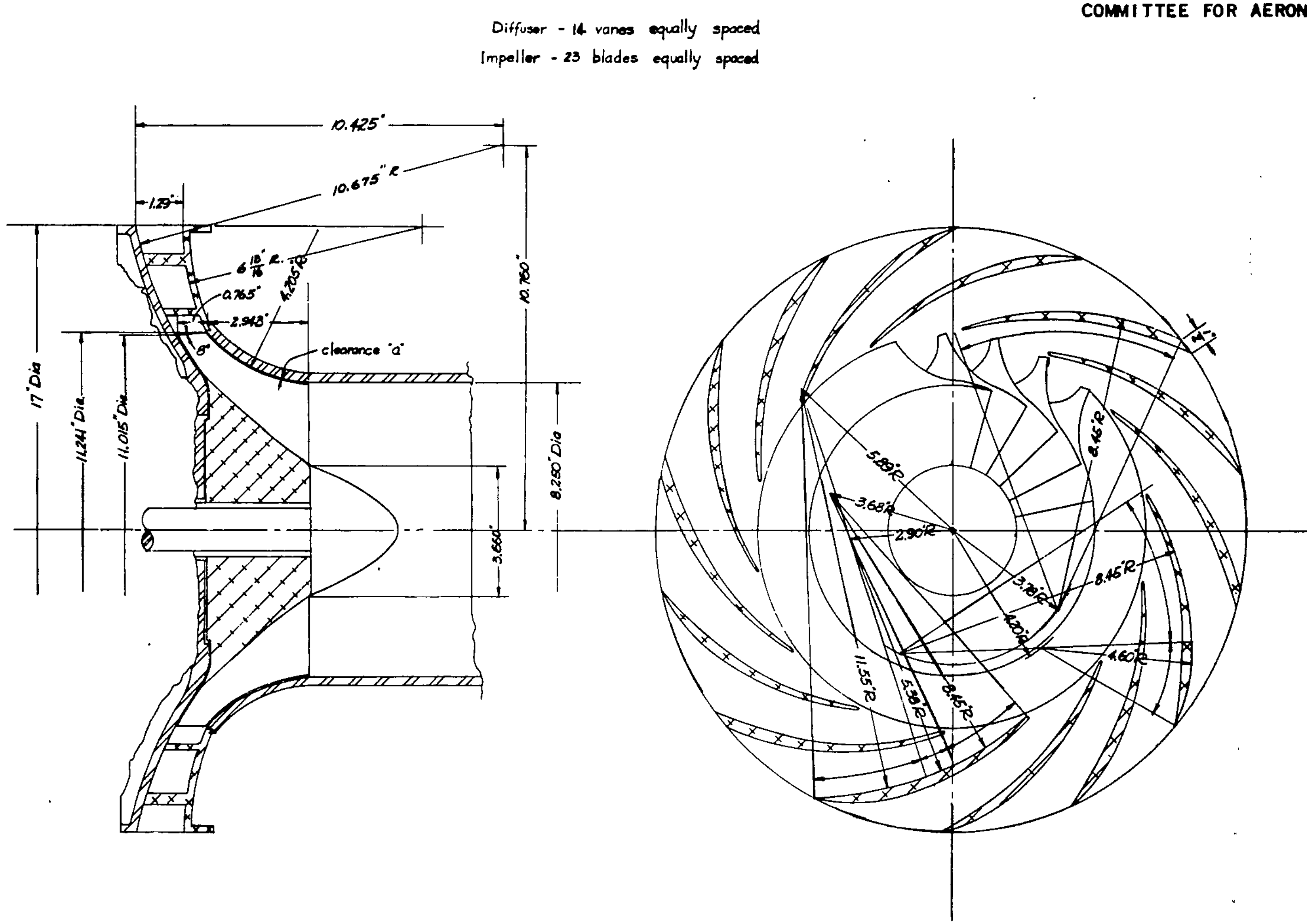


Figure 3. - Assembly of mixed-flow impeller and vaned diffuser showing principal dimensions and clearances.

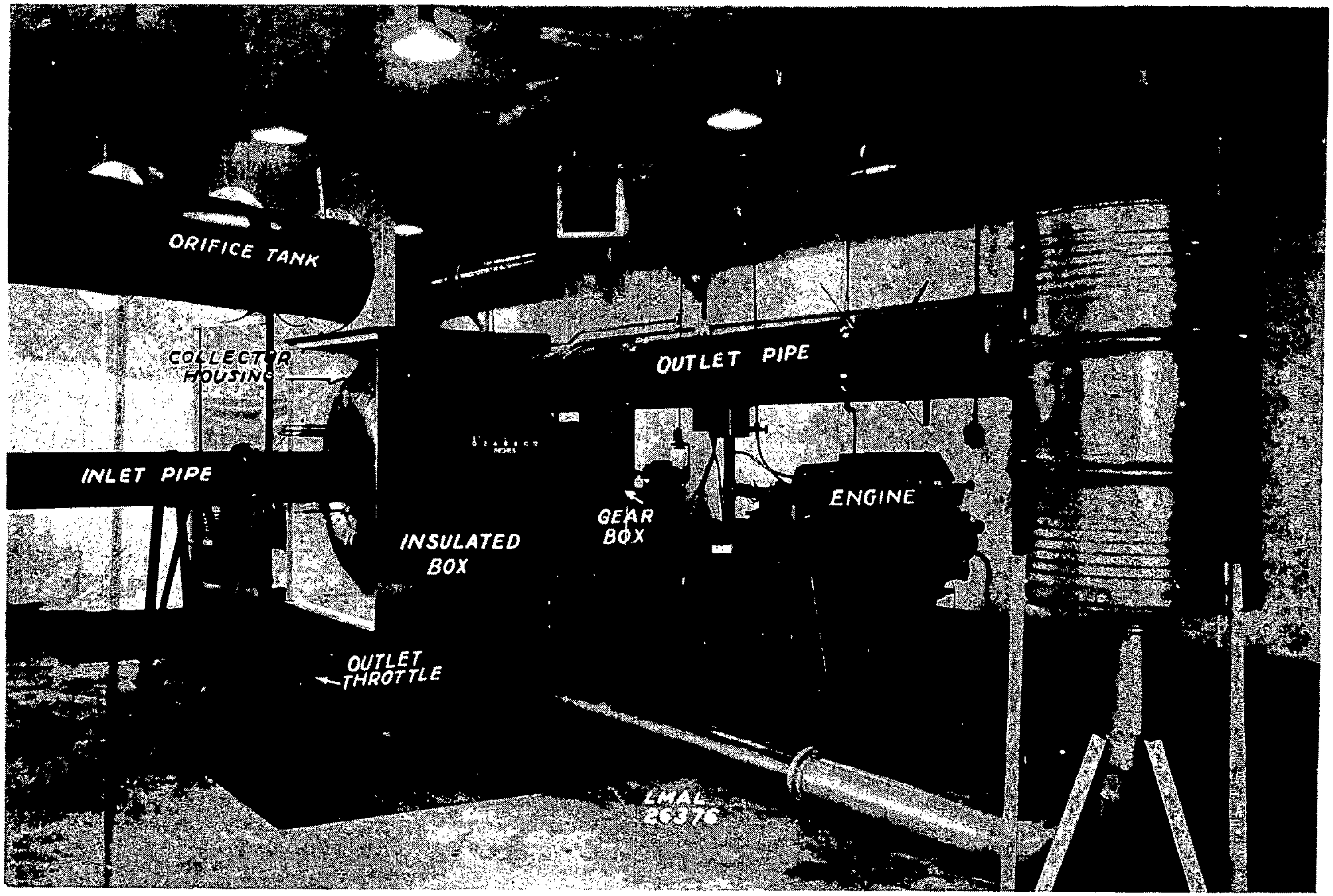


Figure 4. - Test setup for supercharger investigation.

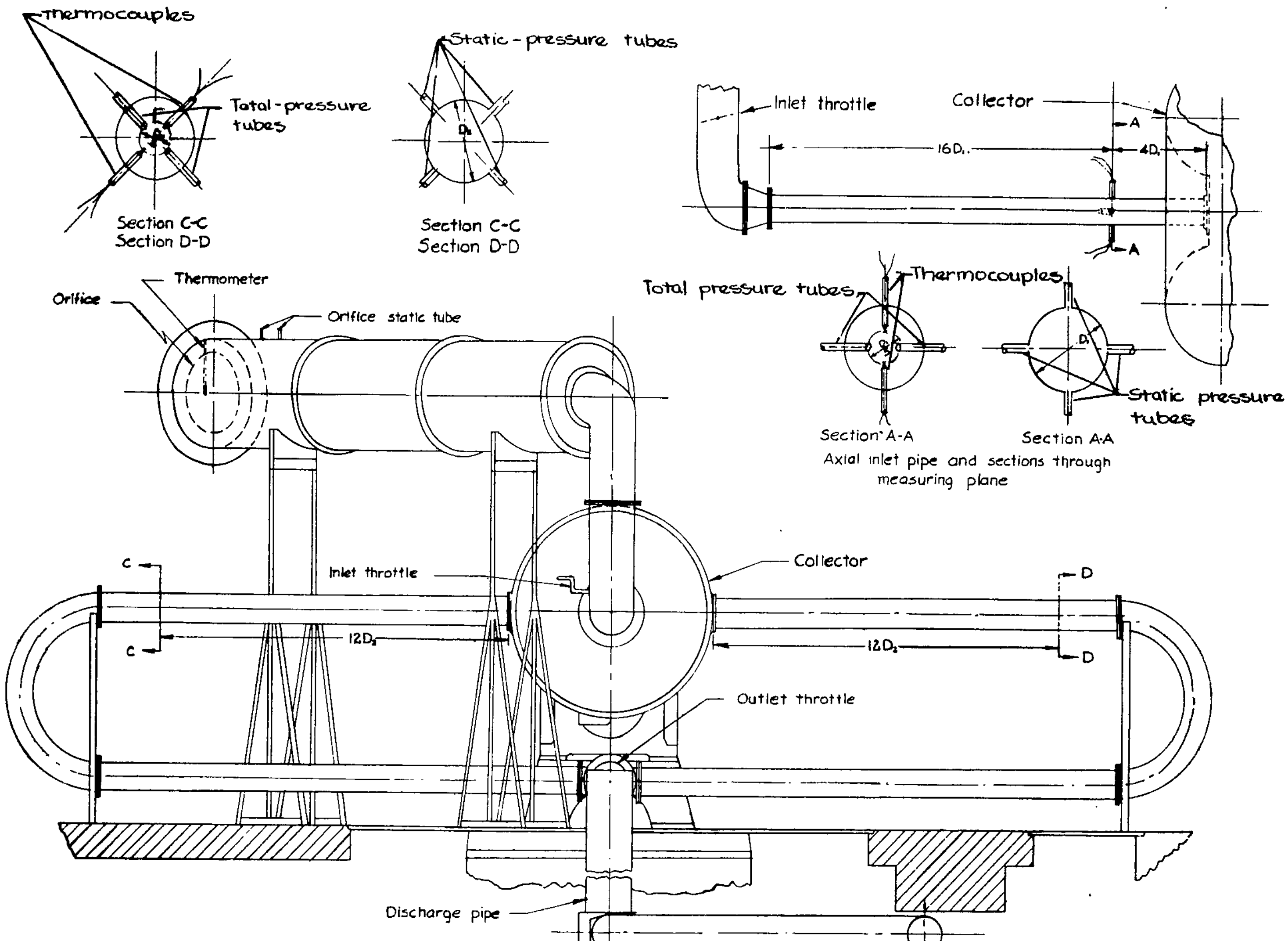


Figure 5. - Location of thermocouples and pressure tubes in supercharger test rig.

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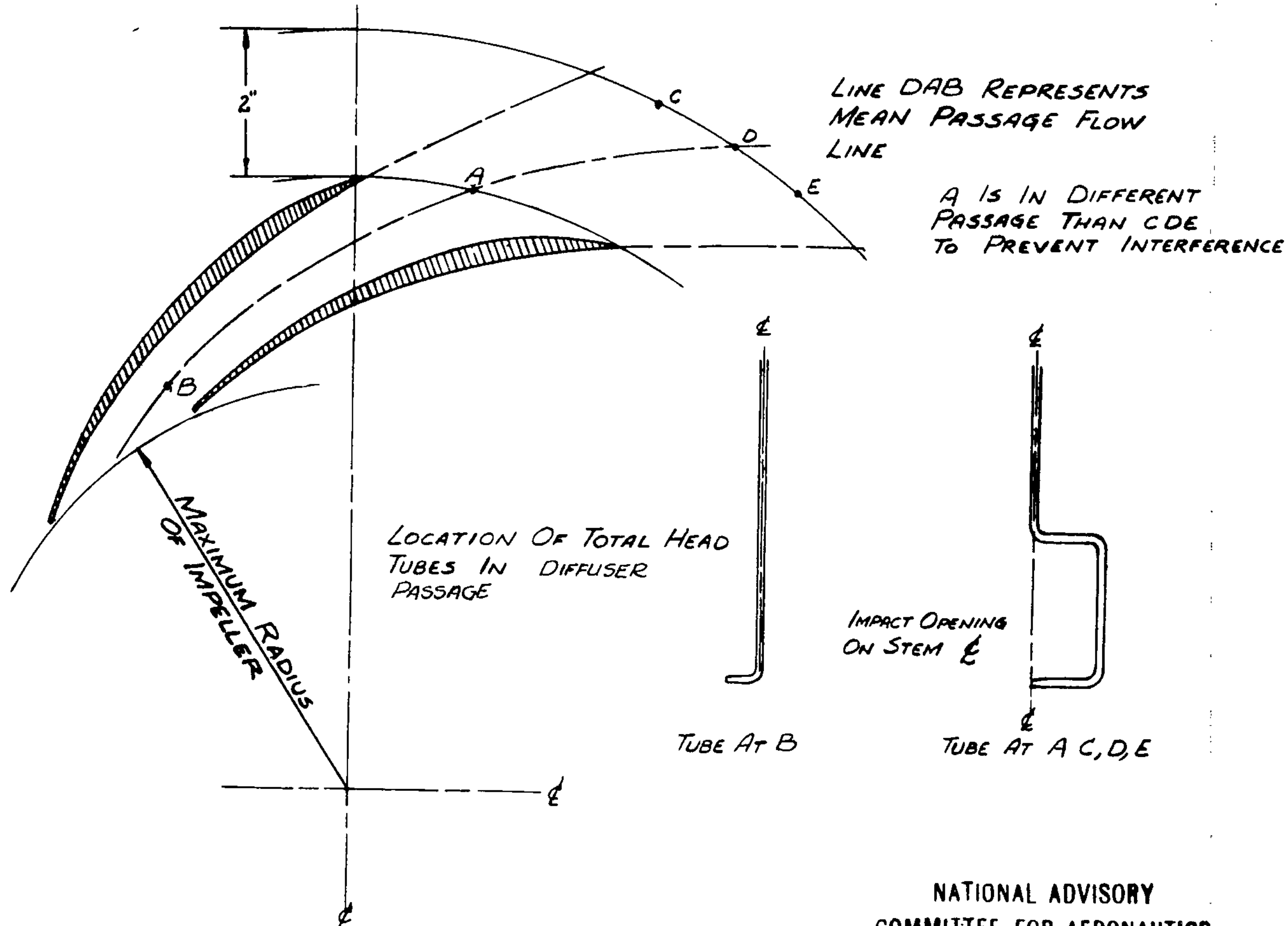

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Figure 6. - Location of survey tubes in diffuser passages.

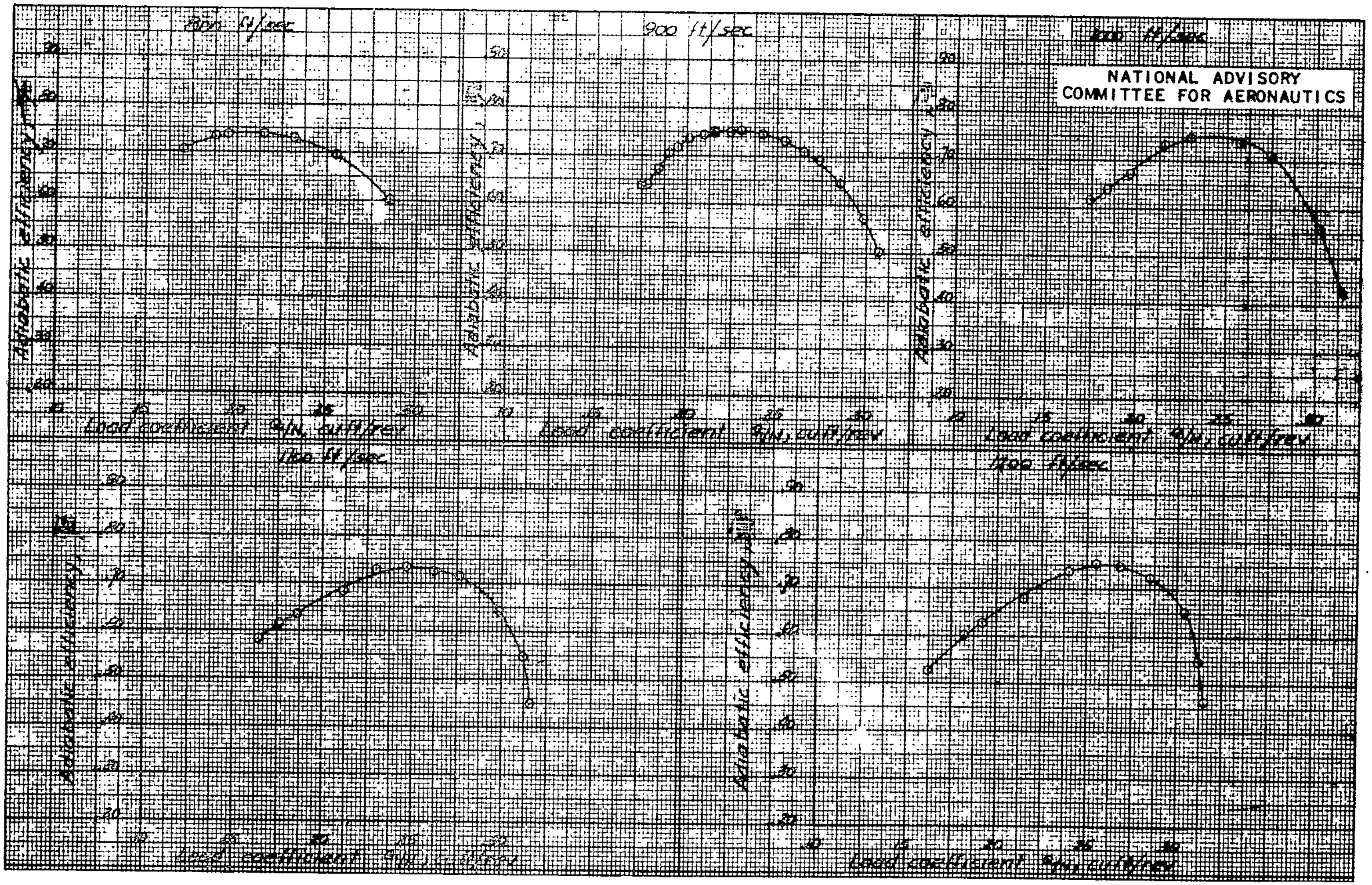

Figure 7. - Adiabatic efficiency of supercharger - 0.070 in. mean frontal clearance.

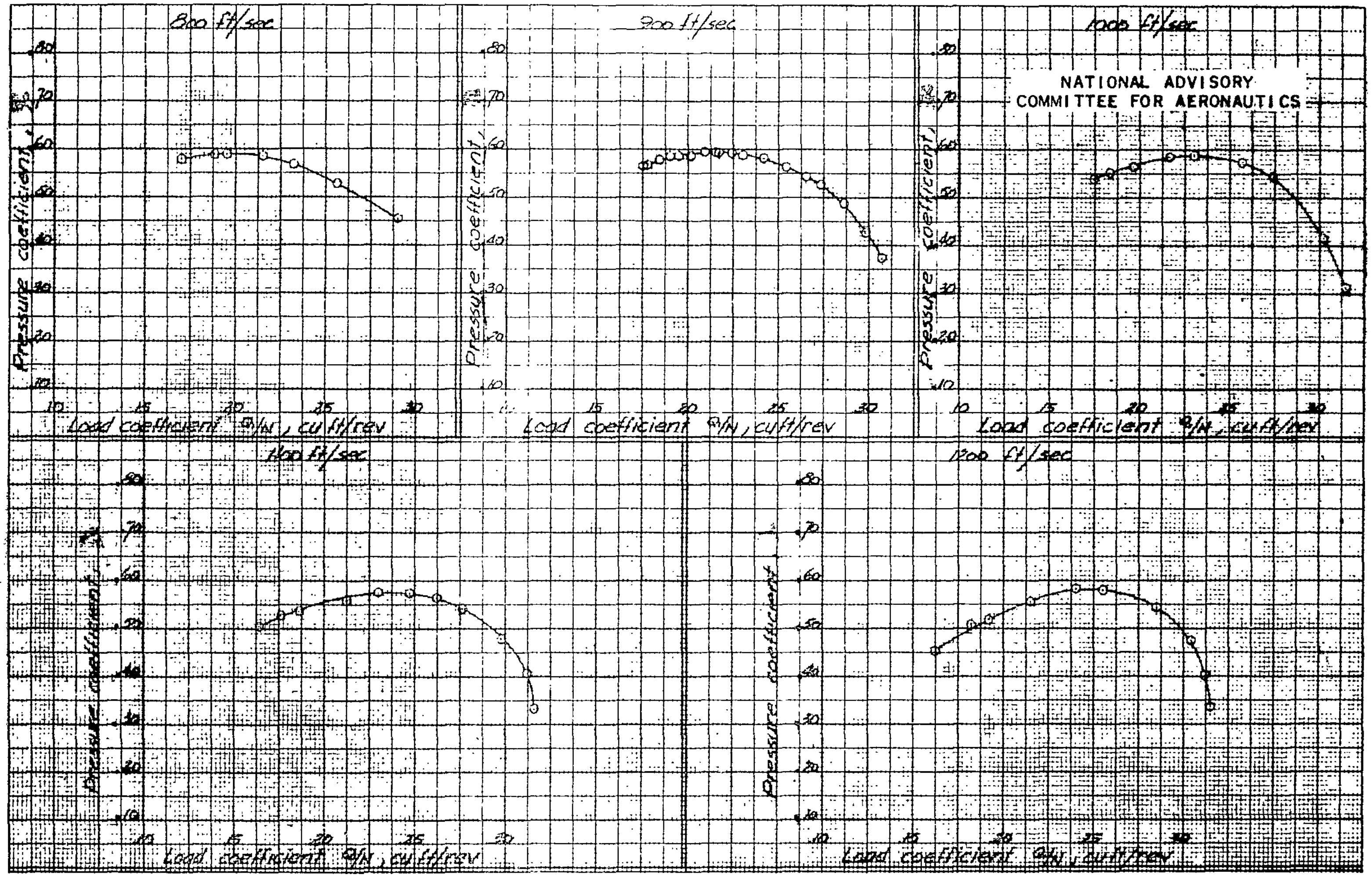

Figure 8. - Pressure coefficient of supercharger - 0.070 in. mean frontal clearance.

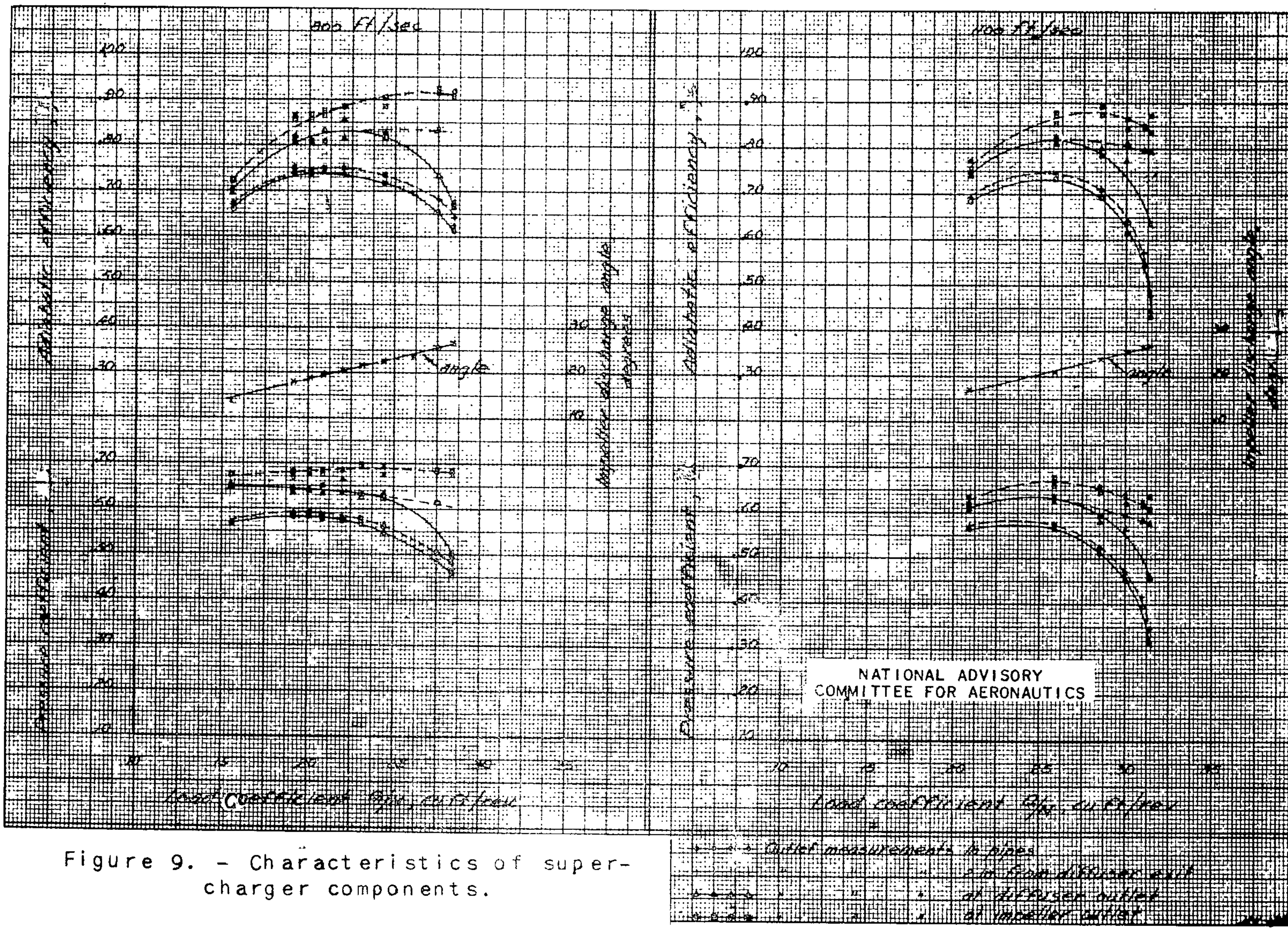

Figure 9. - Characteristics of super-charger components.

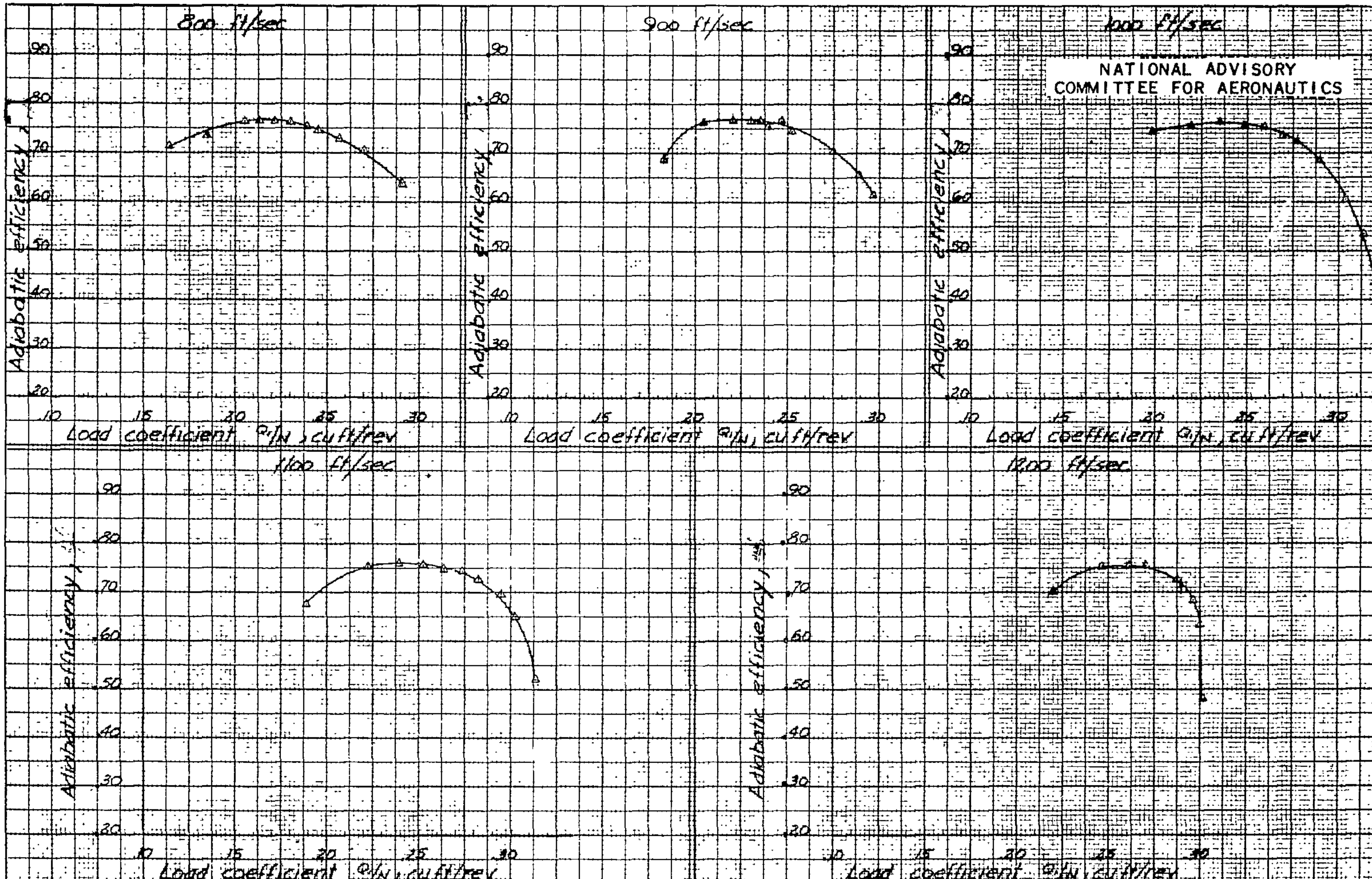

Figure 10. - Adiabatic efficiency of supercharger - .035 in. frontal clearance - tangential outlet pipes.

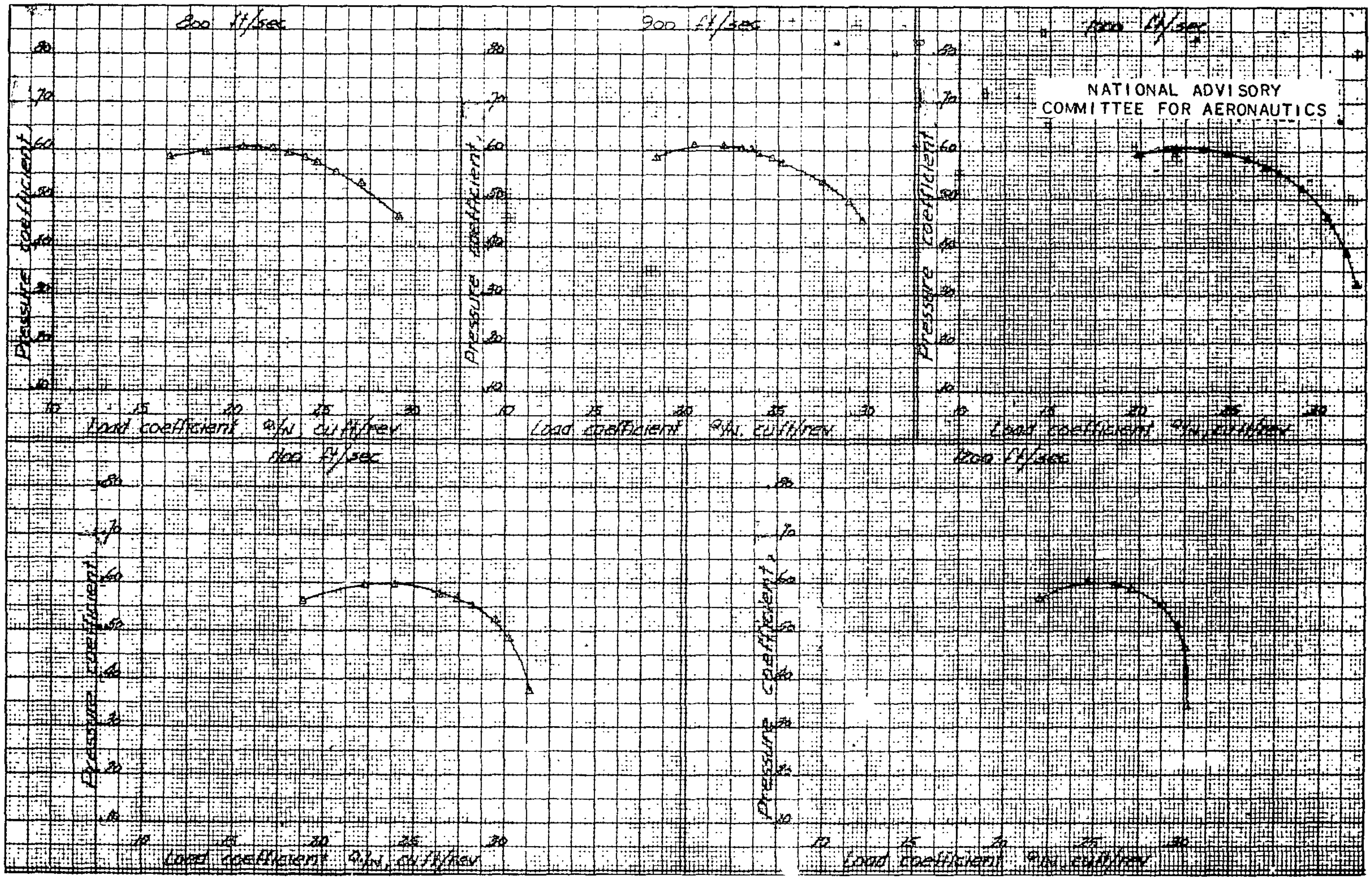

Figure 11. - Pressure coefficient of supercharger - .035 in. frontal clearance - tangential outlet pipes.

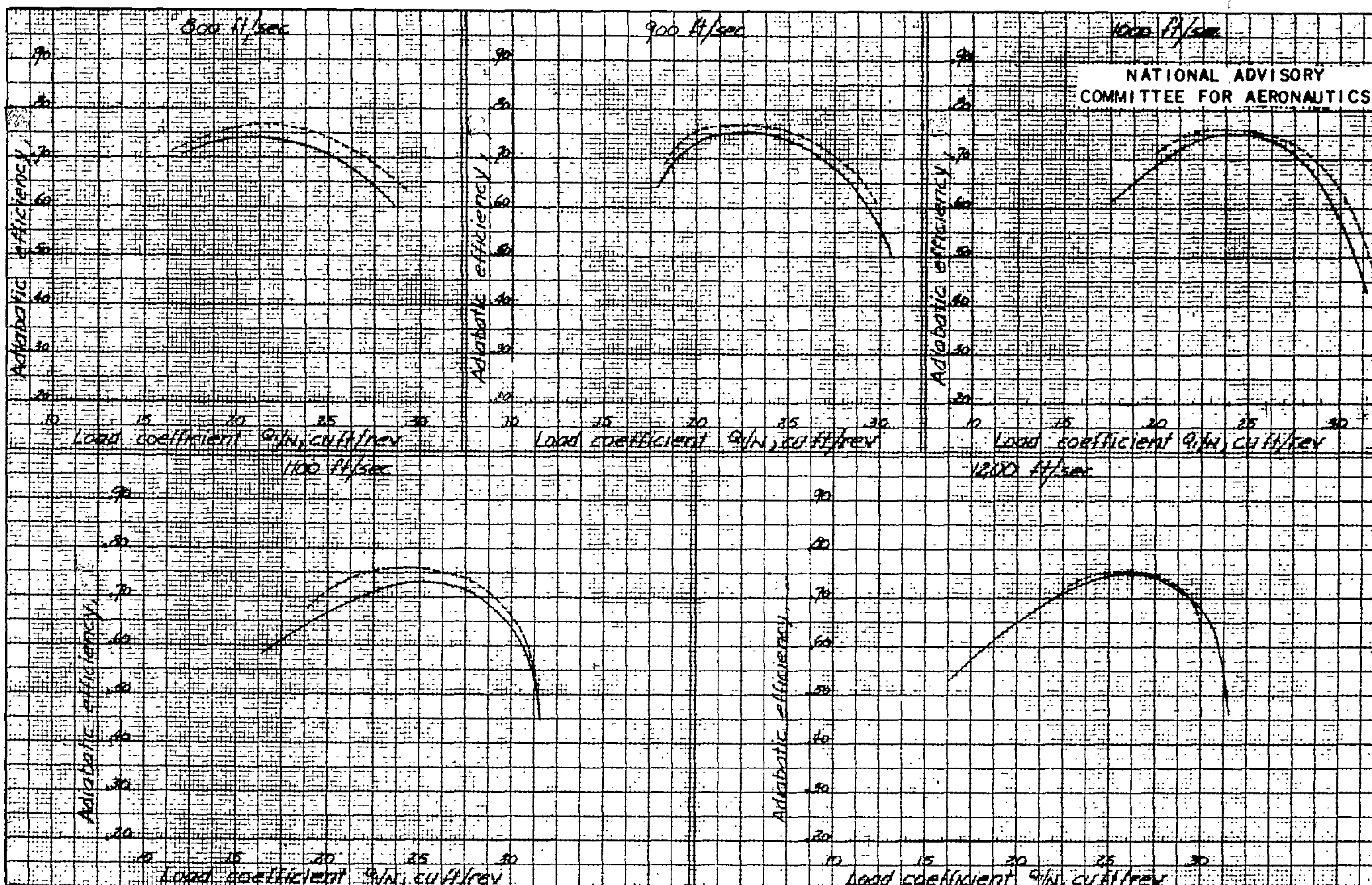

Figure 12. - Comparison of supercharger perfo.mance at .070 in. mean clearance and at .035 in. clearance.

---- .035 in. clearance
—— .070 in. mean clearance

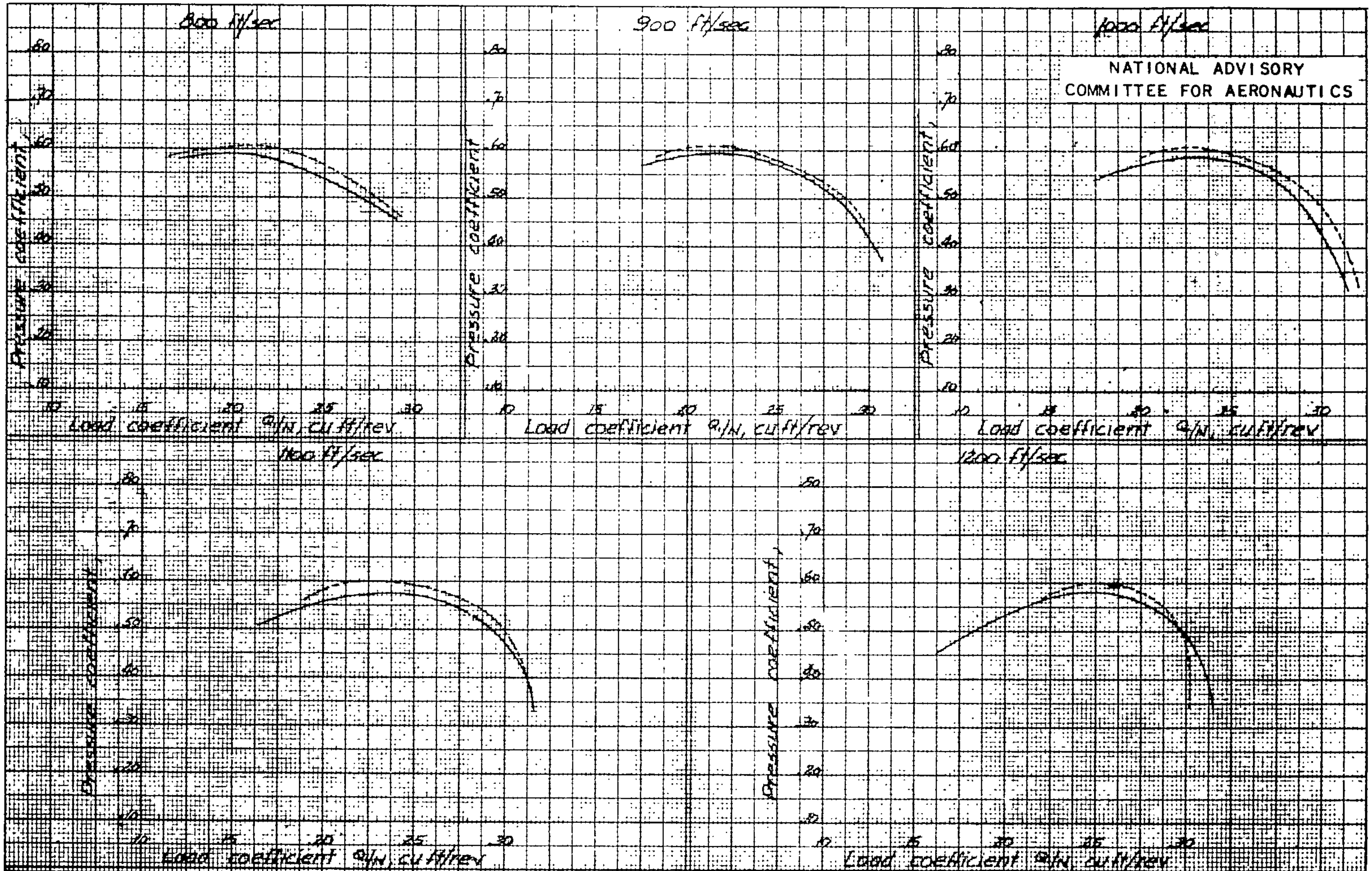

Figure 13. - Comparison of supercharger performance at .070 in. mean clearance and at .035 in. clearance.

---- .035 in. clearance
—— .070 in. mean clearance

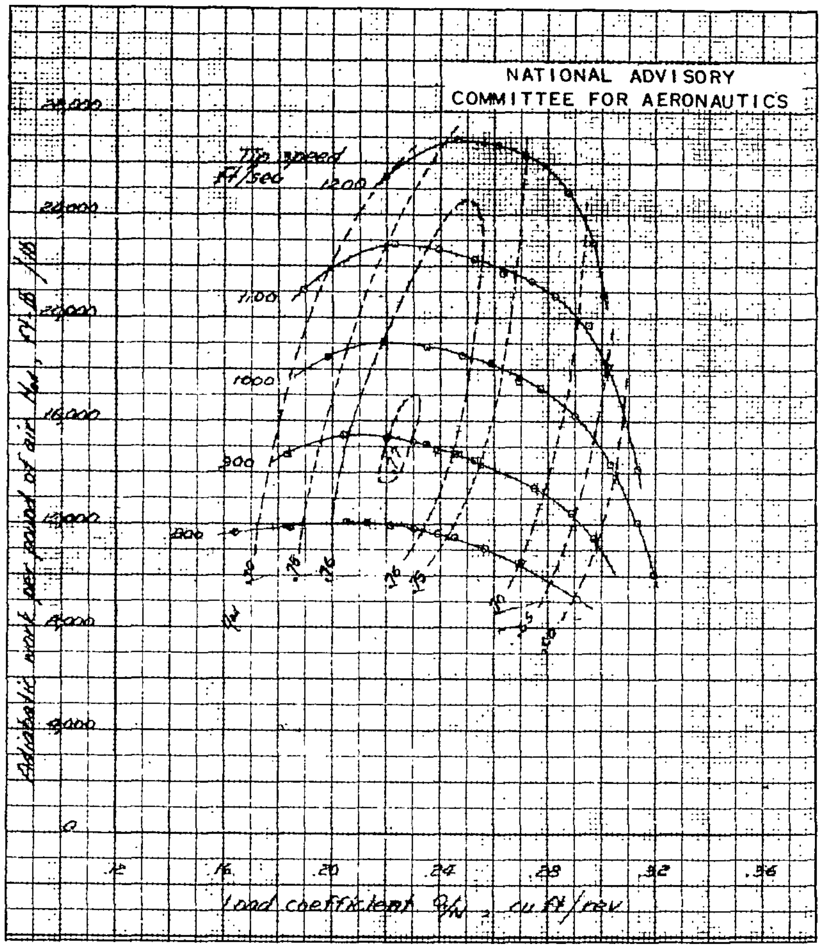

Figure 14. - Characteristics of mixed-flow impeller and vaned diffuser - frontal clearance .035 in.

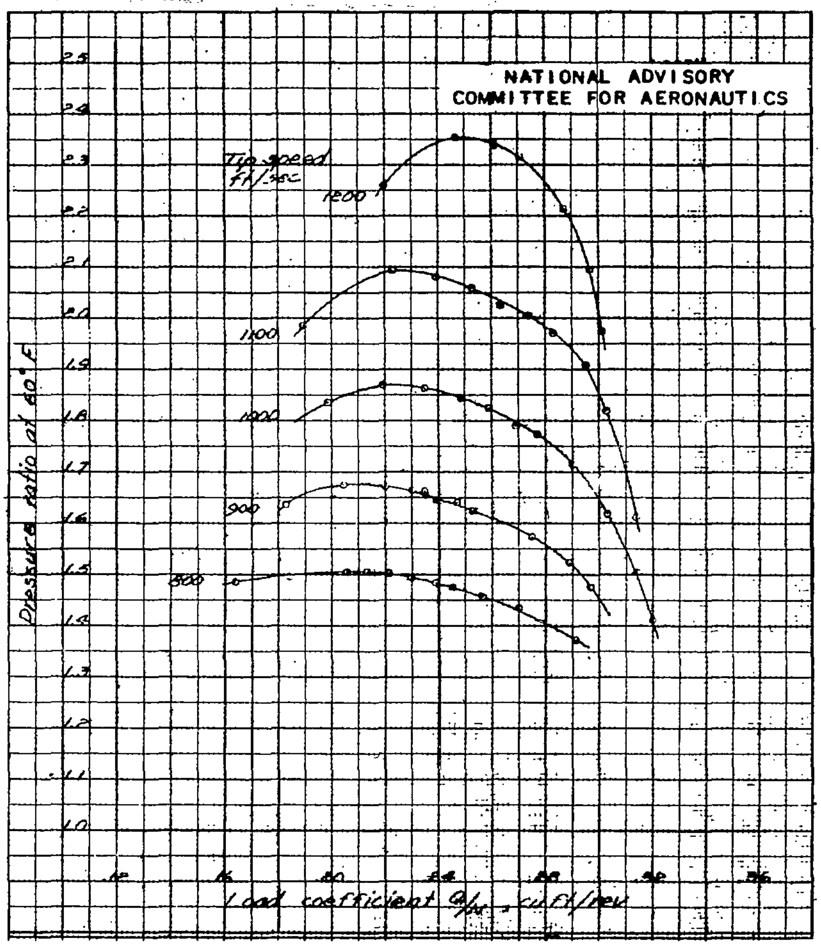

Figure 15. – Pressure ratio of mixed-flow impeller and vaned diffuser at 60° F – frontal clearance .035 in.

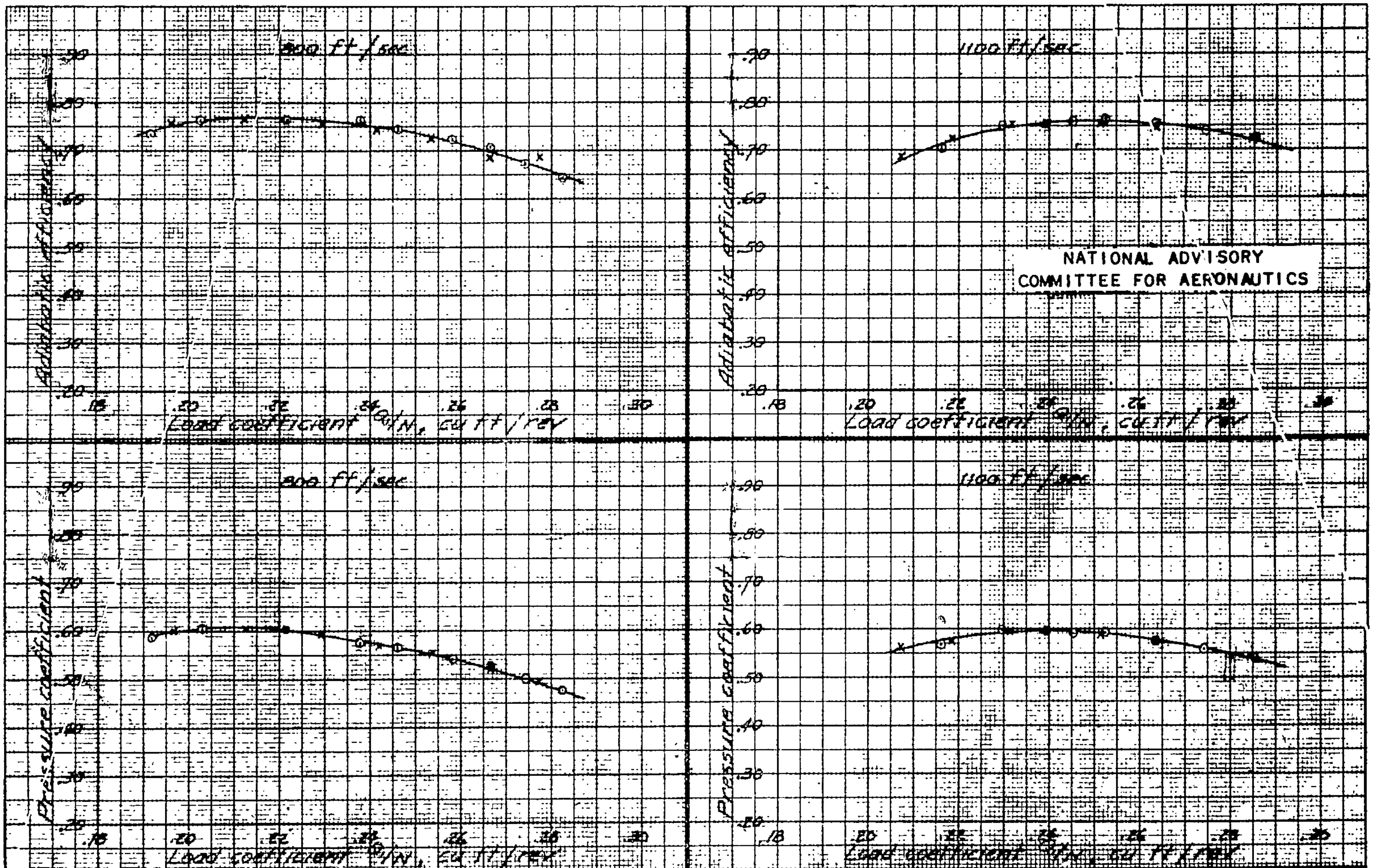

Figure 16. - Comparison of characteristics of supercharger with original impeller and with replacement impeller.

-o—o- replacement impeller -x—x- original impeller

impeller frontal clearance = 0.035" in both cases

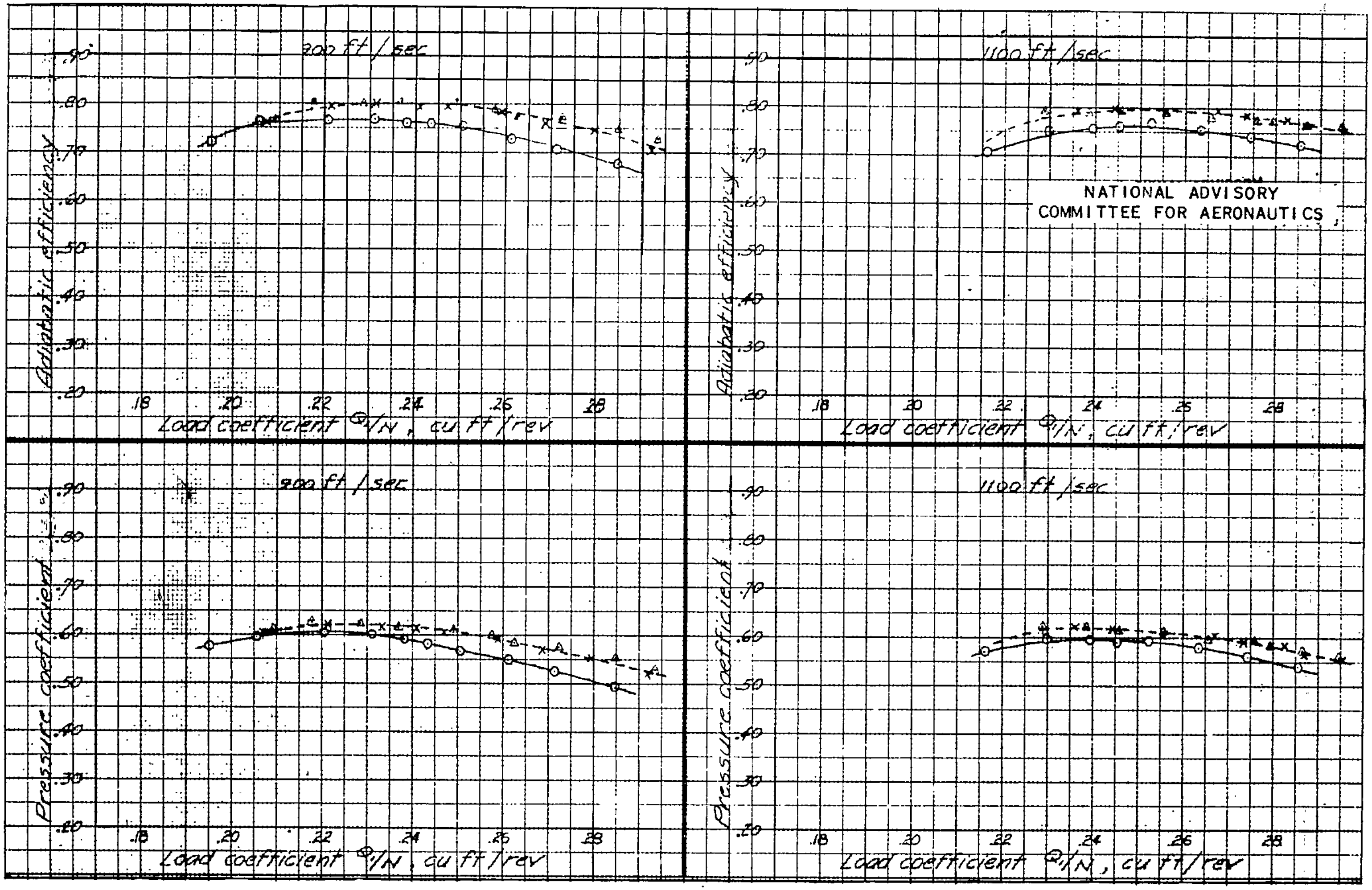

Figure 17. - Performance characteristics of supercharger with vaneless diffuser extensions

—×— diffuser with 27" O.D. vaneless extension

—△— diffuser with 35" O.D. vaneless extension

impeller frontal clearance = 0.035" in all cases